Study of Electromagnetic Forming of Cylindrical Workpieces Based on Equivalent Electrical Circuit

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Abstract* – Electromagnetic forming is a method of metal working by plastic deformation, under the action of forces acting on the conductor in a rapidly varying magnetic field obtained by discharging a battery of condensers through a forming coil. The analytical treatment of the process in terms of equivalent circuits as well as field analysis method has been established since the end of 1970s. The main disadvantage of such approaches is that they cannot be easily applied to more complicated coil geometries, which are often used in industrial applications. In this paper, electromagnetic forming is modeled by a theoretical model of an electromagnetic forming installation takes into account the induction effects with in conductors, the induction effects of work piece motion, and the dynamic behaviour of workpiece material. We present the numerical simulation of transients in an electromagnetic forming installation of cylindrical conductors using PSPICE software.

***Keywords:* electromagnetic forming, equivalent circuit.**

I. INTRODUCTION

The elements of the electromagnetic forming scheme that is shown in Fig. 1 are the following: the rectifier (**R**) that ensures the charging of capacitor bank (**C**) at voltage U_0, the switch (spark gap **E**) that allows the discharging of the stored energy through the forming coil (**B**), intense impulsive electromagnetic forces that appear producing the workpiece deformation.

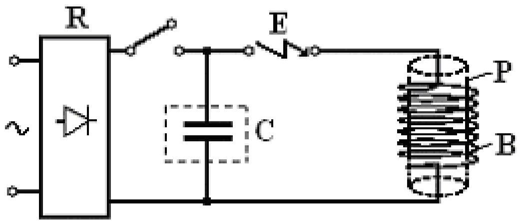


Fig. 1. Electrical scheme and principle of the electromagnetic forming installation: the case of compression thin wall metallic tubes placed within cylindrical coil.

II. ELECTRICAL EQUIVALENT SCHEME

A. Assumptions

The obtaining of electrical equivalent scheme with concentrated parameters for electromagnetic forming devices is difficult because of very complex phenomena that are produced within coil – workpiece assembly.

The frequency of damping oscillating current that appear after the starting of capacitor bank discharge, usually, is around tens kHz. Then, the effect of nonuniform distribution of current in massive conductors (transient skin effect) is non negligible and will be taken into account in equivalent electrical scheme.

The displacement of the workpiece during the deformation is considered by the occurrence of an electromotive force induced by the motion. The expression/value of this e.m.f. is function of equation of workpiece movement, which assumes the solving of mechanical equations of forming, with a high degree of difficulty.

Another phenomenon difficult to be analyzed is the "end-effect", that means the non-uniform distribution of electromagnetic field at the ends of the forming coil.

Finally, the currents that flow through conductors determine the heating of these conductors by Joule losses and as a consequence the variation of material (electrical, magnetic and mechanical) parameters and circuit parameters within equivalent scheme.

The references for EMF domain at this moment are unable to provide a complete model that takes into account all these phenomena. Mostly, these phenomena are neglected and given results are not in accordance with experimental data.

B. Simplified equivalent scheme

The analysis of electromagnetic forming device is performed using equivalent electrical circuit. If we neglect the skin effect and the movement of the workpiece, we can obtain a first variant of equivalent scheme, shown in Fig. 2, where the forming coil – workpiece assembly is equivalent as a transformer.

The switch is replaced with an ideal circuit breaker and the resistivity and inductance of feeding conductors are included in R_{ext}, respectively L_{ext}. Forming coil is modeled by R_1 and L_1 components, workpiece by R_2 and L_2 and coupling by mutual inductance L_{12}.

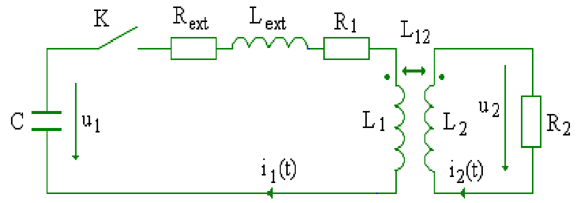


Fig.2. Simplified electrical equivalent circuit of electromagnetic forming installation

Circuit parameters are considered constant in time that it's not happens in real situation, when these values are modified by geometry and material properties changes (that are modified by heating and deformation of the workpiece).

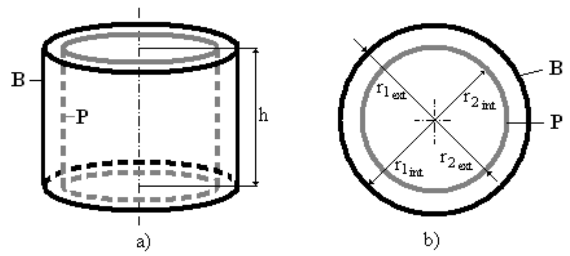


Fig.3. Geometry and dimensions of forming coil and workpiece, for the case of crimping thin wall metalic tubes: a) lateral view; b) upper view

Calculus relations for the case shown in Fig. 3.

$$R_1 = \frac{2\pi \cdot r_{1ext} \cdot N_1}{\sigma_1 \cdot a \cdot b} \qquad (1)$$

$$R_2 = \frac{\pi (r_{2int} + r_{2ext})}{\sigma_2 \cdot h \cdot (r_{2ext} - r_{2int})} \qquad (2)$$

$$L_1 = \frac{\pi \cdot \mu_0 \cdot r_{1ext}^2 \cdot N^2}{h_1} \qquad (3)$$

$$L_2 = \frac{\pi \cdot \mu_0 \cdot (r_{2int} + r_{2ext})^2}{4 \cdot h_2} \qquad (4)$$

$$L_{12} = k_f \sqrt{L_1 \cdot L_2} \qquad (5)$$

where: $k_f = \left(\frac{2 \cdot r_{1ext}}{r_{2int} + r_{2ext}} \right)^2$, and σ represents electrical conductivity.

C. Influence of deformations and skin effect on equivalent scheme

Electrical equivalent diagram for cylindrical configuration shown in Fig. 3 is possible to be improved including the skin effect and effect of moving, as is presented in [1].

Thus, for primary circuit we can write:

$$u_1 = (R_{ext} + R_1) \cdot i_1 + L_{ext} \frac{di_1}{dt} + \frac{d\varphi_1}{dt} \qquad (6)$$

where the magnetic flux of the coil is expressed:

$$\varphi_1 = \pi \cdot \mu_0 \cdot r_{1ext}^2 \cdot N \cdot \frac{N \cdot i_1}{h_1} - \pi \cdot \mu_0 \cdot r_{2ext}^2 \cdot \frac{i_2}{h_2}) + + 2 \cdot \pi \cdot r_{2ext} N \cdot b_s \qquad (7)$$

In (7) b_s represents the magnetic flux within workpiece wall. If the deformation of the workpiece are small with respect to the initial radius, we may apply the approximation:

$$r_{2ext}^2 = (r_{20ext} + x)^2 \approx r_{20ext} \left(1 + 2 \cdot \frac{x}{r_{20ext}} \right) \qquad (8)$$

where r_{20ext} is initial radius, r_{2ext} is the radius after the deformation and x represents the deformation. Using eq. (7) and (8) equation (6) can be write:

$$u_1 = (R_{ext} + R_1) i_1 + L_{ext} \frac{di_1}{dt} + L_1 \frac{di_1}{dt} - \frac{d}{dt} \left[L_{120} \left(1 - 2 \frac{x}{r_{20ext}} \right) i_2 \right] + \frac{d}{dt} \left[2\pi r_{2ext} N b_s \right] \qquad (9)$$

In the secondary circuit, we can write the equation:

$$u_2 = -\frac{d\varphi_2}{dt} \qquad (10)$$

where $\varphi_2 = \pi \cdot \mu_0 \cdot r_{2ext}^2 \cdot \frac{i_2}{h_2} - \pi \cdot \mu_0 \cdot r_{2ext}^2 \cdot \frac{N \cdot i_1}{h_1}$.

In this case (10) becomes:

$$u_2 = \frac{d}{dt} \left[L_{120} \left(1 - 2 \frac{x}{r_{20ext}} \right) i_1 \right] - \frac{d}{dt} \left[L_{20ext} \left(1 - 2 \frac{x}{r_{20ext}} \right) i_2 \right] \qquad (11)$$

Eq. (9) and (11) are circuit equations that take into account the movement effect. If we include the influence of skin effect, like in [1], we obtain the following equations:

$$u_1 = (R_{ext} + R_1) i_1 + L_{ext} \frac{di_1}{dt} + L_1 \frac{di_1}{dt} - \frac{d}{dt} \left[L_{120} \left(1 - 2 \frac{x}{r_{20ext}} \right) i_2 \right] + \sum_{k=1}^{\infty} 8N^2 R_2 \left[i_1 - i_{p\ 2k-1}^1 \right] - \sum_{k=1}^{\infty} 4NR_2 \left[i_2 - i_{p\ 2k-2}^2 \right] \qquad (12)$$

$$u_2 = R_2 i_2 + \sum_{k=1}^{\infty} 2R_2 \left[i_2 - i_{p\ k}^2 \right] - \sum_{k=1}^{\infty} 4NR_2 \left[i_1 - i_{p\ 2k-1}^1 \right] \qquad (13)$$

$$\frac{di_{p\ k}^1}{dt} = \frac{k^2}{\tau_p} \left[i_1 - i_{p\ k}^1 \right], \quad i_{p\ k}^1(0) = 0, \ k = 1,2,. \ .(14)$$

$$\frac{di_{p\ k}^2}{dt} = \frac{k^2}{\tau_p} \left[i_2 - i_{p\ k}^2 \right], \quad i_{p\ k}^2(0) = 0, \ k = 1,2,....(15)$$

The quantities with 0 indices represent the values in the case with undeformed workpiece, $i_{p\,k}^{1}$ is current in rank k cell from primary, $i_{p\,k}^{2}$ is current in rank k cell from secondary and $\tau_p = \mu_0 \sigma (r_{2ext} - r_{2ext})^2$.

Electrical circuit corresponding to (12)÷(15) is presented in Fig.4 a. Fig.4 b shows a variant with secondary quantities referred to primary. Such variant is most adequate to solving with simulation software codes for electrical circuits (ORCAD, MATLAB / SIMULINK, etc.).

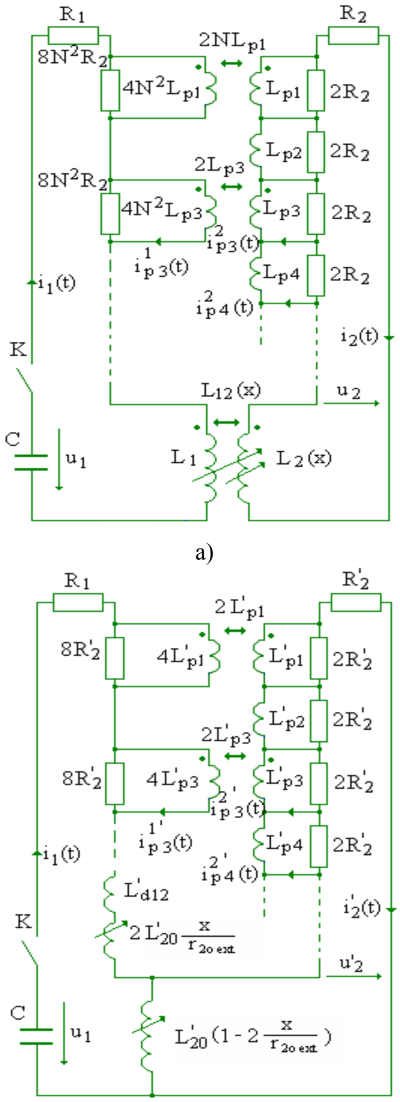


Fig. 4. Equivalent circuit diagram for compression of thin wall tubes: a) the variant with primary and secondary circuit; b) the variant of equivalent scheme referred to the primary circuit

Circuit parameters from Fig. 4 which are not specified yet, are give by:

$$L_2(x) = L_2\left(1 - 2\frac{x}{r_{20ext}}\right)$$

$$L_{12}(x) = L_{120}\left(1 - 2\frac{x}{r_{20ext}}\right)$$

$$L_{pk} = \frac{2 \cdot R_2 \cdot \tau_p}{k^2 \cdot \pi^2} \qquad u_2' = N \cdot u_2$$

$$i_2' = \frac{i_2}{N} \qquad i_{p\,k}^{1\;'} = \frac{i_{p\,k}^{1}}{N} \qquad i_{p\,k}^{2\;'} = \frac{i_{p\,k}^{2}}{N} \tag{16}$$

$$R_2' = N \cdot R_2 \qquad L_{20}' = N \cdot L_{20}$$

$$L_{d12}' = L_{20}'\left(\frac{r_{1ext}^2}{r_{2o\,ext}^2} - 1\right)$$

The variation of geometry dimensions of the workpiece is reflected through the variation of mutual inductance between primary and secondary circuit.

D. Movement equations and deformations

The relation between the strength σ and deformation ε is obtained using a visco-plastic model with consolidation:

$$\sigma = \sigma_0 + \lambda \cdot \varepsilon + \eta \cdot \dot{\varepsilon}^{\delta} \qquad \varepsilon = \frac{x}{r_{20ext}} \tag{17}$$

where: λ is consolidation coefficient, η is viscosity coefficient and δ rate sensivity coefficient.
The equations of motion may be written:

$$\frac{dx}{dt} = v$$

$$\frac{dv}{dt} = \frac{1}{\gamma \cdot d} \cdot p_{em} - \frac{\sigma_0}{\gamma \cdot r_{20ext}} - \frac{\lambda}{\gamma \cdot r_{20ext}^{\;2}} \cdot x - \frac{\eta}{\gamma \cdot r_{20ext}^{\;1+\delta}} \cdot v^{\delta} \tag{18}$$

where x is the radial deformation, p_{em} is the electromagnetic pressure and γ is the material density.

III. ANALYSIS OF EQUIVALENT CIRCUIT USING PSPICE

In order to obtain the PSPICE implementation of the equivalent circuit from Fig. 4 b, we retain a finite number of R-L cells. We use voltage and current controlled source for taking into account the coupling between mechanical and electromagnetic phenomena. We obtain the circuit shown in Fig. 5. The values of circuit components are calculated with next relations:

$$R_2 = N^2 \cdot r_2 \qquad R_3 = 8 \cdot N^2 \cdot r_2$$

$$R_4 = 8 \cdot N^2 \cdot r_2 \qquad R_5 = 2 \cdot N^2 \cdot r_2 \cdot \psi_N$$

$$R_2 = N^2 \cdot r_2 \qquad R_3 = 8 \cdot N^2 \cdot r_2$$

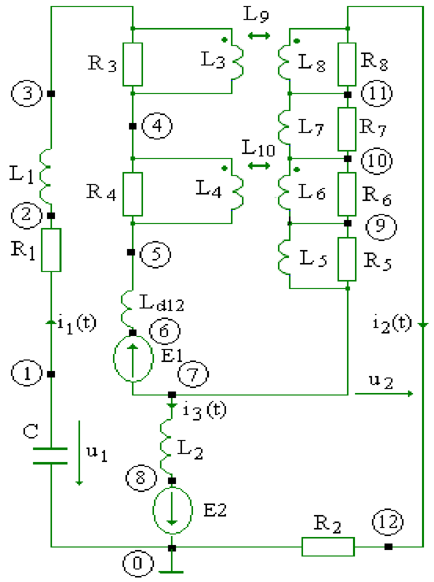
$$R_4 = 8 \cdot N^2 \cdot r_2 \qquad R_5 = 2 \cdot N^2 \cdot r_2 \cdot \psi_N$$

$$R_6 = 2 \cdot N^2 \cdot r_2 \qquad R_7 = 2 \cdot N^2 \cdot r_2$$

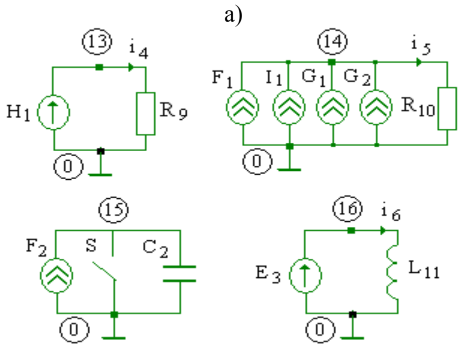
$$R_8 = 2 \cdot N^2 \cdot r_2 \qquad R_9 = \frac{2 \cdot h_1}{\mu_0 \cdot N^2}$$

$R_{10} = 1 \qquad C_1 = 500uF$

The capacitor $C_2 = 1F$ is used for integration the quantity a in order to obtain the speed deformation.



a)



b)

Fig. 5. Implementation of equivalent circuit in PSPICE:
a) equivalent circuit of electromagnetic phenomenon;
b) calculus of electromagnetic pressure p_{em}, acceleration a, strain rate v and deformation x.

$$L_{220} = \frac{\pi \cdot \mu_0 \cdot (r_{20\mathrm{int}} + r_{20ext})^2}{4 \cdot h_2}$$

$$L_2 = N^2 \cdot L_{220}$$

$$L_{d12} = L_{220} \cdot \left(\frac{r_{1ext}^2}{r_{20ext}^2} - 1\right) \cdot N^2$$

$$L_1 = \frac{2 \cdot r_2 \cdot \mu_0 \cdot \sigma_2 \cdot (r_{20iext} - r_{20\mathrm{int}})^2}{\pi^2} = \frac{2 \cdot r_2 \cdot \tau_p}{\pi^2}$$

$$L_3 = 4N^2 \cdot L_1 \qquad L_4 = 4N^2 \cdot \frac{L_1}{9}$$

$$L_5 = N^2 \cdot L_1 \frac{\psi_N}{\alpha_N} \qquad \alpha_N = \frac{\frac{\pi^2}{8} - (1 + \frac{1}{9} + \frac{1}{25})}{\frac{\pi^4}{96} - (1 + \frac{1}{81} + \frac{1}{625})}$$

$$\psi_N = \alpha_N \cdot \left[\frac{\pi^2}{8} - (1 + \frac{1}{9} + \frac{1}{25})\right]$$

$$L_6 = N^2 \cdot \frac{L_1}{9} \qquad L_7 = N^2 \cdot \frac{L_1}{4}$$

$$L_8 = N^2 \cdot L_1 \qquad L_9 = 2N^2 \cdot L_1$$

$$L_{10} = 2N^2 \cdot \frac{L_1}{4} \qquad E1 = \frac{2N^2 \cdot L_{220}}{r_{20ext}} \cdot v \cdot i_3$$

$$E2 = \frac{2N^2 \cdot L_{220}}{r_{20ext}} \cdot v \cdot i_1 \qquad E3 = i_2 \cdot (2 \cdot i_1 - i_2)$$

$$E4 = v = V(15) \qquad G1 = \frac{1}{\gamma \cdot (r_{20ext} - r_{20\mathrm{int}})} \cdot i_4$$

$$G2 = -\frac{\lambda}{\gamma \cdot r_{20ext}^2} \cdot x \qquad G3 = -\frac{\lambda}{\gamma \cdot r_{20ext}^{(1+\delta)}} \cdot v^{\delta}$$

$$I1 = -\frac{\lambda}{\gamma \cdot r_{20ex}} \qquad F1 = \frac{dv}{dt} = i_5$$

The numerical simulation of transients in an electromagnetic forming installation using PSPICE software.is present in Fig.6.

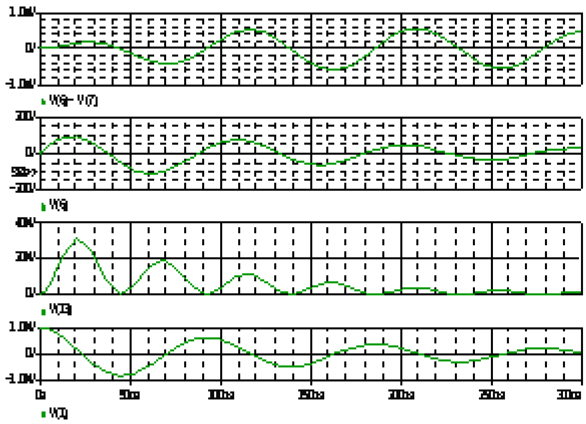


Fig. 6. The numerical of transient in a electromagnetic forming instalation using PSPICE.

IV. CONCLUSIONS

This approach is very useful in numerical analysis of electromagnetic forming devices, giving the main characteristics of these installations.

The results presented in the paper are in a good agreement with the data from references.

ACKOWLEDGMENTS

This work was supported by Romanian Ministry of Education and Research, Grant CNCSIS A 1319/2007, 34GR/21.05.

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